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Coastal risk adaptation: the potential role of accessible geospatial Big Data

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ABSTRACT

Increasing numbers of people are living in and using coastal areas. Combined with the presence of pervasive coastal threats, such as flooding and erosion, this is having widespread impacts on coastal populations, infrastructure and ecosystems. For the right adaptive strategies to be adopted, and planning decisions to be made, rigorous evaluation of the available options is required. This evaluation hinges on the availability and use of suitable datasets. For knowledge to be derived from coastal datasets, such data needs to be combined and analysed in an effective manner. This paper reviews a wide range of literature relating to data-driven approaches to coastal risk evaluation, revealing how limitations have been imposed on many of these methods, due to restrictions in computing power and access to data. The rapidly emerging field of 'Big Data' can help overcome many of these hurdles. 'Big Data' involves powerful computer infrastructures, enabling storage, processing and real-time analysis of large volumes and varieties of data, in a fast and reliable manner. Through consideration of examples of how 'Big Data' technologies are being applied to fields related to coastal risk, it becomes apparent that geospatial Big Data solutions hold clear potential to improve the process of risk based decision making on the coast. 'Big Data' does not provide a stand-alone solution to the issues and gaps outlined in this paper, yet these technological methods hold the potential to optimise data-driven approaches, enabling robust risk profiles to be generated for coastal regions.

1. Introduction

Decision-making in coastal regions needs to be based on sound science and accurate information. Access to appropriate 'information' has been outlined as comprising a vital component within the coastal management process [1]. Data and information form the basis of comprehensive mapping and analysis of coastal risk [2–5]. However, there exists a vast body of data for coastal zones, and the volume and variety of datasets requiring collation, organisation, and subsequent analysis can prove overwhelming. If progress is to be made in this area a new paradigm must be developed for data, information and knowledge management. Emergent information and computational techniques hold potential benefits in the realisation of this goal. The rapidly evolving field of 'Big Data' and associated analytical approaches are proposed to be well-suited to facilitate such decision-making.

This paper focuses on coastal risk adaptation, the role of information, and potential application of Big Data solutions within this domain. This is addressed through assessment of literature dated from 2000[1] to 2017, focussing especially upon the application of data-driven approaches to coastal zone management. This has permitted emergent themes to be highlighted and investigated, providing a new understanding as to the efficacy of these methods. As yet, there have been only limited studies completed in relation to coastal Big Data approaches, yet those which do exist suggest there is considerable scope for application of these technologies to enable the generation of robust environmental risk profiles for coastal regions [3,6–8].

At the outset, it must be stated that this work cannot represent a comprehensive evaluation of all materials published concerning coastal decision support approaches, within the seventeen-year time-period reviewed. This work instead sets out to characterise and reflect upon emergent developments and, in so doing, presents a discerning representation of relevant key works, providing a structure to support an appraisal of developing opinion concerning the complexities surrounding coastal risk assessment. The publications addressed are categorised within three themes, namely: coastal risk adaptation, data-driven approaches, and the application of Big Data to coastal management. Table 1 (in Section 7) provides an overview of issues addressed within this research in relation to these three themes. It is considered that these themes provide a useful foundation for addressing the developments in this new area, with each selected publication exemplifying pertinent issues from the current debate.

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[1] The cut-off point, of the year 2000, was selected so to incorporate some important coastal management developments made in the early years of the new millennium.

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2. Coastal risk and adaptation

2.1. Vulnerability/hazards

Sustainable management approaches in coastal zones are challenged through the wide-ranging, dynamic hazards threatening the status quo in these regions. Hazards have been defined by authors, such as Kron [12, p. 1369], as representing 'the threat posed by natural forces that cannot be influenced….. beyond mankind's control'. Muro et al. [13, p. 4] define a hazard as 'the potential to cause harm (or intrinsic capacity to cause damage)'. In an anthropocentric sense hazards are seen in general as exerting a potential threat to humans and their welfare. Of the naturally occurring coastal hazards, flooding and erosion are the two most significant, and are therefore focused on primarily within this paper. Flooding of coastal systems in particular is considered 'one of the most frequent and damaging natural hazards, affecting countries across the globe' (UNISDR [32] cited in [11]). Nevertheless, impacts are also generated from human activity in coastal areas and the ocean. Unsustainable overuse of maritime resources represents a significant concern, and land-based pollutants (such as sewage and industrial wastewater) are major threats to coastal ecosystems [12].

Coastal hazards lead in turn to societal vulnerabilities, affecting properties, persons and infrastructure. Smit and Wandel [13, p. 284] state the term vulnerability is used to describe 'the estimated net or residual impacts (being the initial impact costs, minus net adaptation savings)'. For England and Wales, Defra [17, p. 104] estimated that approximately '100,000 properties, having a total value of £8 billion, in areas without protection could be eroded in the next century' with 1 million coastal properties being at risk of flooding, with an estimated value of £130 billion.

Population growth within the coastal zone has been widely cited as a catalyst factor raising levels of vulnerability [16,17]. Natural hazard losses can be related directly to the number of people living in risk prone areas, especially where a large number of people, assets and complex infrastructure are concentrated in single vulnerable locations.

2.2. Risk

In acknowledging coastal hazards and associated vulnerabilities, the nature and extent of coastal risk can be identified. Risk may be defined as the probability of a given hazard occurring, factored by the severity of its consequences [1,9,14,18–24], thus:

$$Risk = Probability\ x\ Consequence \tag{1}$$

Risk represents 'the main instrument and criteria leading to coastal zone management policy' [19]. The Tyndall Coastal Simulator project [25], identified for a case study site in East Anglia that flood risk is predicted to grow exponentially during the 21st century, whilst erosion risk is predicted to remain relatively constant. Jongman et al. [11] state that, in the Netherlands, exposure to flooding has increased by 300% over the last 50 years, as economic value in coastal areas has risen at a rate above that of the national average. Poor planning on the coast and unsustainable natural resource use has been cited as major factors exacerbating a wide range of environmental risks, such as those relating to natural processes, Climate Change induced hazards and pollution [16].

2.3. Impacts

Within the progression of the coastal risk cycle, hazards create vulnerabilities, which in turn lead to the propagation of these hazards, resulting in consequences, which can be labelled 'impacts'. The term impact 'implicitly deals with severity, intensity, or duration of the effect' [28, p. 69], Impacts can become compounded in some instances because of human attempts at adaptation. As a result 'Coastal Squeeze' can occur, as habitats and natural coastal features become caught between defences and rising sea levels and so become lost at accelerated rates [15,27].

One implication of human intervention is that many stretches of coast, lying adjacent to protected areas, have become sand-starved [28]. This concurs with the most apparent impact from physical coastal processes being the landward transition of the shoreline, becoming especially apparent when extreme events occur, such as the North Sea Storm Surges of 1953 and 2013 [29,30]. Damage arising from natural disasters has been reported to increase in recent times as a result of capital accumulation in flood-prone areas [20].

2.4. Adaptive measures

Adaptations have been termed: 'adjustments in a system's behaviour and characteristics that enhance its ability to cope with external stress' [15, p. 282]. Conflict is almost inevitable where continued development in coastal areas requires stability, whilst natural processes involve change [31]. As a result, humans who wish to develop coastal sites are required to adapt to natural processes.

In terms of physical adaptations, conventional coastal adaptations can be split into groupings of 'hard' and 'soft' measures. Hard adaptation measures are generally regarded as semi-permanent installations on the coast. Examples of these are seawalls, revetments, groynes, and breakwater sills. Soft adaptation measures include beach feeding (recharge), dune building, and 'Managed Realignment' [28]. Soft measures are deemed to be those designed to work with natural processes [23]. In the UK, Defra [14] have outlined the need to 'work with natural processes' and to use a 'wide range of risk management options', including softer adaptation measures. Furthermore, in enacting *Making Space for Water*[2] [15], Defra is reported to be using ecosystems services in some areas, instead of relying on hard measures (in tackling flood and coastal erosion risk) [32].

In economic terms people begin to rely on coastal protection structures, making their property more valuable [31]. In this sense government can be seen to provide inverse incentives to invest in hazardous areas through the provision of protection [11]. For the right adaptive strategies to be adopted, rigorous evaluation of the available options is required [33]. This evaluation hinges on the availability and use of suitable datasets.

2.5. Coastal risk assessment – the role of information

Building on notions of coastal risk, it becomes apparent that a core driving aspect of managing the coastline is the completion of reasoned risk assessments. Within risk assessments, hazards need to be identified, together with estimations of their probability, and quantification of the impacts these hazards will have on vulnerable areas. This enables adaptive management strategies to be developed. Advances in computing power can prove critical in this process as responses to events can be altered by data-driven modelling [1]. Without this a situation of inappropriate development of coastal land can arise. Generally though, increased construction on the coast is seen to result in long-term damage to the environment and increased risk from flooding and erosion [31]. Therefore, in making decisions about future developments on the coast it is critical to evaluate the full range of risks.

In their first response to, *Making Space for Water*, Defra [14] emphasise how risk information must drive activities, highlighting the specific requirement for inclusion of better data on the consequences of coastal flooding and erosion. In relation to coastal partnerships in England, Milligan et al. [34] argue that a fresh approach should better incorporate flood and erosion risk assessments in its planning phases.

[2] Making Space for Water is a key document relating to government coastal policy in England and Wales, published in 2004 [15].

Yet this is not simple, and difficulties for risk assessors are seen to involve a choice between different subjective estimates of risk, and ultimately real risk being perceived as an 'inherently unknowable entity' [16, p. 4]. In addressing these problems we need to determine where the most rational analysis of the most relevant evidence has been completed [1]. In particular, factors such as 'the location of a development is crucial in determining flood risk' [20].

Kron [9] elaborates on the elements required for inclusion in risk assessments, stating that risk components included must account for: physical, economic, social, political, psychological, and cultural factors. Risk assessments may thus involve development of what Smit and Wandel [15, p. 282] labelled 'Vulnerability Indices', seen as an aid to identification of adaptation strategies. The reasoning underlying this is that coastal threats need to be predicted so that communities and civil protection agencies are able to respond and so hazard reduction 'measures can be put in place to reduce the risk' [35].

The scale at which risks are measured, and the methodology underlying aggregation of data variables used to calculate risk, can prove problematic to the generation of representative risk assessments. Jongman et al. [36] concur with this, concluding that caution should be exercised 'when using aggregated land-use data for flood risk assessment', as this has resulted in over/under-estimation of flood damages. Moreover, Kron [9] highlights how integrating data for large spatial areas, in terms of average intensity, may obscure values derived from modelling of flood losses. However, the methodology of many risk assessments for the coast have incorporated some form of aggregation [37–39]. Therefore, it is evident that progress is required in this area.

One theme neglected in many coastal risk assessments relates to recognition of the role of ecosystem services. Yet ecosystem based coastal management approaches are now deemed essential [40]. Arkema et al. [41] argue that evaluation methods focusing on the role of natural defences lag behind those focusing on hard adaptation measures. To ensure representative coastal risk evaluations take place more thorough syntheses are called for, incorporating a diverse range of statutory data, such as climate scenarios, demographic information and ecological data, alongside hazard models. Ramieri and Hartley [39] stress the importance of moving beyond an anthropogenic perspective, considering ecological needs and the socio-economic context as a hazard in itself. This more holistic approach to risk assessment fits in with the wider aims of Decision Support Systems (DSS) outlined by Westmacott [42], as seeking to improve 'our understanding of inter-relationships between the natural and socio-economic variables', thus improving decision making.

The process of accurate risk analysis, and importantly how the results of this can be conveyed to the public, can serve to increase risk perception. If risk awareness is low, negative results can ensue, such as an increase in properties being built and purchased in areas prone to flooding [16,20]. Risk perceptions are said to be shaped by a wide range of factors, socioeconomic, demographic and cultural; given this, it is imperative that risk assessments account for a wide range of elements, otherwise risk perception bias can ensue [20].

3. Big Data

The terminology of Big Data, relates not only to the handling of large volumes of data, but refers also to broader data issues such as the ability to manage concurrently a wide variety of data formats, with the incorporation of high currency and even real-time (high velocity) data [43,44]; allied to which are a new generation of analytical and data processing capabilities. Central to the concepts surrounding Big Data are the multi-node computer infrastructures employed, enabling the collective storage of large volumes of data in a distributed and scalable manner [45]. Big Data approaches can enable the large, diverse databanks associated with comprehensive environmental risk mapping exercises, to be incorporated successfully within a single modelling framework.

Of particular importance to coastal risk evaluation is how Big Data tools and associated technologies offer the potential to tackle issues of scale, data density, and incompatibility of data formats for data covering large geographical areas and time periods [46–48]. The following sections address data and information use and requirements (for coastal management), with a review of existing research in this area. Following this, in Section 6, an assessment is provided of the current application of Big Data to this domain.

4. Data driven approaches to managing risk in the coastal zone

4.1. Coastal management

Coastal Management has historically been 'characterised by a fundamental lack of understanding of natural coastal processes' and a view that the 'land sea boundary is fixed' [46, p. 587]. In recent times, governments worldwide have been identifying the need to prioritise scientific understanding of coastal regions, which are inherently dynamic. The role of information and accurate science is recognised as important for the governance of ocean and coastal resources [50,51]. Therefore, to achieve knowledge-based decision-making, a data-driven approach is fundamental and can provide the means to generate a clearer understanding of the processes at work on the coast [1].

When solutions are required to issues which span across scales of governance, then problems can occur due to a lack of systematic environmental data and metadata exchange between nations and the international community [51]. Key to Integrated Coastal Zone Management (ICZM) are the associated data management initiatives, which include best practice guidelines for data exchange and metadata standards, and which contribute to ICZM being able to maximise and bring into focus value derived from environmental data [40,52]. Implementation of data management through spatial planning is therefore deemed a typical aspect of ICZM which is seen to contribute to generation of an improved knowledge base [53].

4.2. Spatial data and land planning

Spatial management is viewed a significant factor contributing to understanding and addressing the levels of risk experienced in coastal regions [21]. Flood risk in particular, is a key aspect of spatial planning [15]. In China, Li et al. [3] researched the consequences of rapid urbanisation in the coastal city of Haikou. They revealed a large, emerging disparity between developments in different areas within the same coastal zone. They concluded that this indicates a requirement for planning policy to ensure the sustainability of future coastal developments, as land utilisation is a key human activity increasing vulnerability on the coastline. Low awareness of risk can be a causal factor leading to inefficient spatial developments [23]. A core aspect of coastal management is regarded to involve creation and implementation of a risk-based framework, reducing vulnerability through controlling future development [19].

Filatova and Veen [19] argue that it is the government's responsibility to inform coastal populations of risk in these regions, but due to their inadequacy in doing so, inefficient allocations of land have resulted and as a consequence demand for protection has increased in line with rising economic values [20,54]. This problem has been reduced to a cycle, illustrated in Fig. 1, in which property is constructed in vulnerable locations in the coastal zone, resulting in increased demand for protection; following installation of (temporary) protection, a false sense of security is generated and the density of habitation increases further, thus causing risk to rise once again. Filatova and Veen [19, p. 165] argue that this 'self-reinforcing cycle that has a negative effect on flood risk'.

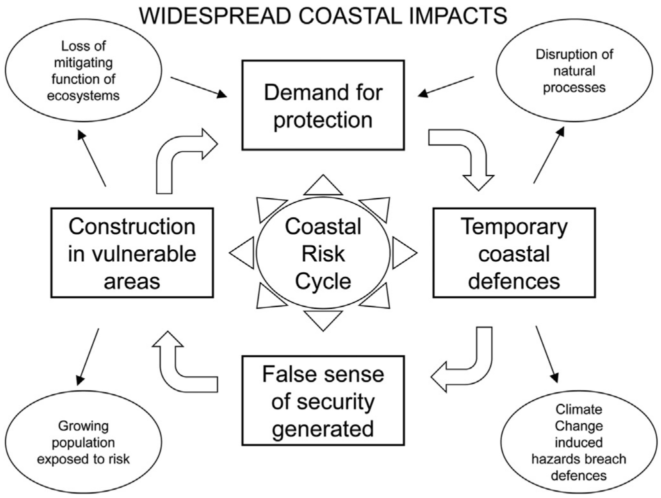

Fig. 1. Coastal risk cycle.

4.3. From data to knowledge

Coastal Decision Support Systems (DSS) which are used for testing management strategies and vulnerability assessments, hinge on the availability, accuracy and resolution of appropriate data. Linking 'high resolution data, numerical flood models and visualisation tools provide opportunities for society to respond to …. flooding events' [54, p. 238]. In Ireland, data was identified as a core requirement within the Cork ICZM plan, being recognised as providing the foundation of a knowledge base for climate adaptation and spatial land use planning [53]. Yet when assembling such large quantities of data, many challenges are encountered. Despite there being significant bodies of data made freely available via Open Data platforms, utilisation of this data is not always straightforward for non-specialists. In their study Dyer and Millard [52] drew attention to some of these issues, which they linked to the use and exchange of coastal data. Yet much progress has been made in this field since publication of their seminal paper, and the current momentum of the Open Data movement, combined with advances in web-mapping tools are supporting an increase in access to data, presenting new analytical opportunities [56].

The issue of scale can present specific challenges [57]. It is one of the clear drivers necessitating the use of Big Data technologies. In assessing coastal vulnerability and risk a requirement has emerged to draw on the high level of detail offered by comprehensive localised datasets, yet also to combine this with the enhanced perspective gained from conducting analysis at a regional or national level [38]. To achieve this requires technical approaches to be implemented, able to contend with substantive volumes of 'high density' geospatial data (such as that generated by Lidar systems and satellite sensors), as well as large attribute rich datasets from sources comprising, for example, collections of static, legacy data. In the past, however, this has proved problematic due to restrictions in data availability, storage and processing power [46]. Nevertheless, it is now possible to draw on distributed, networked, dynamic data sources and services, which can potentially enable such an enterprise to be realised.

Generation of knowledge in this domain is reliant on data relating to the coast being continually collected and analysed. The UK's first Marine and Coastal Policy Forum in 2011 outlined that, to enable evidence-based policy making, it is necessary to secure improved data access, sharing, and its utilisation in DSS approaches [58]. There are increasing volumes of data now becoming available, spurred on by Open Data initiatives such as data.gov.uk,[3] and frameworks such as the INSPIRE Directive [59], which can provide policy makers with new opportunities to make informed decisions [14, p. 1245]. Yet the technology utilised to enable collection, processing and sharing of data is rapidly evolving and becoming obsolete as successive technologies emerge [52]. This necessitates consideration of new Big Data tools and techniques, such as those discussed in Section 6.

4.4. Big Data and the INSPIRE Directive

Within a European context, the INSPIRE Directive [59] is a key facet in the adoption of Big Data techniques in support of European Community environmental policies. In considering issues relating to environmental (coastal) data access, sharing and use within decision making, it is valuable to look to some general aspects of INSPIRE which hold global relevance. INSPIRE sets out a framework for a Spatial Data Infrastructure (SDI), designed to facilitate co-ordination and implementation of spatial information for policy purposes. It comprises of protocols developed to aid interoperability of metadata, spatial data sets and services, and network services and technologies. INSPIRE also includes agreements on data sharing, use, coordination, monitoring mechanisms, and procedures. This is achieved through five guiding principles within the Directive such that: data should be collected once and maintained at the most appropriate level; that it must be possible to combine seamlessly and share spatial data from many sources across the EU; that it must be possible for spatial data to be shared between all levels of government (e.g. recognising the merits of the 'reuse of public sector information (PSI)'); that spatial data needed for good governance should be freely available; and that it should be easy to discover and evaluate which spatial data is available, and any usage restrictions made apparent.

Through INSPIRE, data specifications are adopted across over 30 themes with societal or environmental relevance (such as sea regions, oceanographic/geographical features and hydrography). These specifications permit national data repositories and geoportals to implement a common interface to aid the interoperability of their data holdings throughout the European Community. Keay et al. [60] describe the process of moving national scale terrestrial data repositories towards INSPIRE compliance, with related case studies of best practice ([61], p. 179–183). INSPIRE has established mechanisms enabling extensive quantities of information to be interoperated, integrated and analysed, permitting interrelationships between natural and socio-economic factors to be revealed. Essentially this can work to improve the role of evidence within decision-making. The Directive allows a 'multi-view' across layers of interactions between the SDIs and their users. In relation to this current research this is especially pertinent given the wide ranging themes needing to be considered within coastal risk assessments (requiring integration of marine and terrestrial datasets), and the many stakeholders involved in the coastal management process [62].

5. Existing coastal risk adaptation studies

5.1. Collaborative coastal projects within Europe

Many large scale, collaborative studies have been undertaken in the field of coastal risk adaptation, drawing together expertise and resources from industry, the public sector and academia [27]. Within England the Tyndall Coastal Simulator[4] and iCOASST[5] are two recent projects, focussing on issues of coastal vulnerability and modelling of

[3] The Data.gov.uk resource [95], is a British Government Open Data Portal, which was launched in 2010.

[4] As part of the Tyndall Coastal Simulator project, the SCAPE tool, developed by Walkden and Hall [96], was applied to the North Norfolk coast [97,98]. The SCAPE tool focuses on drivers of coastal change such as sediment transport and coastal engineered features.

[5] The iCOASST project [99], built on work completed within the Tyndall Coastal Simulator. It went on to further understanding of coastal processes with case study sites in Suffolk and Liverpool [67].

the physical processes taking place in the near-shore environment. A wide range of projects addressing similar themes have been completed at a European level. Examples include PEARL,[6] THESEUS,[7] C-SCOPE[8] and RISC-KIT.[9]

5.2. Studies focusing on coastal risk

Much research has focussed specifically on coastal risk. Filatova and Veen [19] completed a study focusing on land use change on the coast, concentrating on a case study in Northern Holland and using an Agent Based Model (ABM) approach. The approach was concerned with how interactions between different actors affect land use configuration. The study is important, illustrating how economic and human behaviour data may be combined with other data, such as geomorphology, to model and predict land use change. A study by Jongman et al. [11] also focused on the human aspect of coastal risk, using detailed property level data to enable enhanced decision making on the coast, in relation to flood risk financing at a national scale. The study demonstrates the benefits of combining both scale and detail (noted in Section 4.3). The methodology employed involved combining different spatial scales, using Open Source data from a national property database. The level of detail used was reported as not being common, and the study concluded that aggregated land use data fails to represent accurately changes in property density in urban areas. Property level data, when collated for large areas and combined with hazard datasets, however was shown to enable national level risk mapping.

A wider comparative study by Villatoro et al. [35], incorporated four case studies, and covered open beach study sites in England, Italy, Spain and Bulgaria, considering vulnerability to flooding and erosion. The study established an interdisciplinary methodology for estimating quantitative risk at the study sites. Geographical Information Systems (GIS) were used within some of the case studies to combine and analyse a wide variety of data [35]. Both the Italian and English case studies illustrate the benefits of methods using real data to assess the effectiveness of existing adaptation measures. The study concluded that natural and man-made coastal defences are both crucial in delimitation of the 'extent of coastal erosion' and floods. This concurs with the work reported by Heip et al. [27].

In the UK, outside academia, in 2001 the government commissioned a *Foresight review of future flooding* [18]. This set out to provide a vision for coastal defence and flood policy between 2030 and 2100. Cross-cutting analysis of economic, social and environmental impacts acted as a powerful driver, resulting in recommendations for future nature-based adaptation measures. The review clearly sets out a justification for future data-driven research and model creation. Following the Foresight Review, the National Trust undertook an independent project entitled Shifting Shores [63]. This revealed that, between 2005 and 2014, buildings were still being constructed in areas vulnerable to flooding and erosion, despite the existence of prohibitive planning laws. The study concluded that evidence-based assessments are needed to identify vulnerable locations and urged for more details of coastal risk to be provided in future planning guidance.

5.3. Coastal decision support systems and vulnerability assessments

There are several projects which have reported the creation of coastal risk and vulnerability assessment tools, also often referred to as Decision Support Systems (DSS). DSS approaches were adopted in many collaborative projects, such as THESEUS and RISC-KIT [33,64]. A DSS is a computerised system incorporating a knowledge base or database [42]. The DSS approach covers a wide variety of fields, including socio-economic and ecological factors. Yet Westmacott's study identified how many past attempts have failed in this respect, as they have not produced results relevant to the economic or political context in which they operate.

DESYCO [65] (Decision Support System for Coastal climate change impact assessment) is a regional, GIS-based DSS, focusing on climate change hazards and ICZM. Of the DSS approaches evaluated by Ramieri and Hartley [39], DESYCO was identified as one of the approaches which held the most potential for coastal vulnerability assessments in European seas. The application of GIS aided the project in enabling visualisation and comparison of assessments. Yet the project was disadvantaged by the need to include heterogeneous data sources, formats and spatial scales [39]. Consequently, the inability of the DSS to handle large volumes and varieties of data was seen to constrain this project. This is an issue which Big Data tools can potentially address directly. In this sense, Big Data solutions can possibly enable the benefits of some suitable DSS methods, as in this case, to be unlocked.

In a paper by McLaughlin and Cooper [38], the authors outline the application of the Multi-scale Vulnerability Index (MVI) DSS. The project involved case studies considering three contrasting scales of application in Ireland: national, regional and local. Many issues already highlighted were drawn out from this, including data availability, comparability problems at different scales, and the need to include socio-economic data in assessments (topics also addressed by Bigagli [57]). The correct representation of scale is an issue that has traditionally limited vulnerability assessments. McLaughlin and Cooper [38] reveal how incompatible results have been generated from past assessments at different scales. This is explained in terms of the need, yet inability, to combine local level, high density datasets within larger scale assessments. Some important local level variations are reported to have been masked because of oversimplification within national level assessments. As Jongman et al. [4] McLaughlin and Cooper [38] acknowledge, simplification and aggregation have proven a problem in past studies. Yet due to limitations imposed by data availability, storage and processing power, incorporation of high density datasets has frequently not been possible in past DSS implementations [39]. This highlights the requirement to seek technical solutions, such as those offered in the field of Big Data.

One significant ongoing project that utilises the MVI methodology is the Natural Capital project, in which the InVEST tool was developed [37]. The hazard index, which the InVEST tool creates, includes a typology relating to the role ecosystems play in protecting the coast. Arkema et al. [66] applied this tool to the entire coast of the USA, revealing how important natural habitats are for the protection of coastal areas. The InVEST tool has produced useful insight, but the index it generates has failed to account for interactions between the typologies upon which it is based. The Natural Capital Project acknowledges [37], that the geometric mean of the seven variables considered in the model, can over simplify the complex, dynamic interaction between coastal processes. Unlike the Tyndall [2] and iCOASST [67] projects, the InVEST model does not consider 2D, hydrodynamic or sediment transport processes, in the nearshore region [37].

5.4. The role of GIS within coastal risk studies

Due to the geospatial characteristics of coastal risk, GIS are widely regarded as suitable tools to apply to coastal risk assessments [17]. GIS have been used extensively within vulnerability assessments and DSS.

[6] The PEARL [100] project commenced in 2013 and is still underway (2017) [101]. The project focusses on extreme hydro-meteorological events, and examines holistic risk assessments, including cascading effects.

[7] The THESEUS project [102] ran between 2009 and 2013 and focused on a number of study sites across Europe, representing a range of coastal conditions [33].

[8] C-SCOPE [103] ran as a cross-border cooperation programme in Northern Europe [94].

[9] RISC-KIT [104] is another European collaboration, running from 2013 to 2017. It represents a consortium made up of 18 partners from 10 European countries and two international organisations [64].

For example, in relation to the THESEUS project, Zanuttigh et al. [33] reported how GIS based tools can be adopted as an efficient technical solution, supporting decision making within coastal risk management, and further how GIS can be used as a platform to enable the combination of social, economic and environmental data, facilitating scenario creation. Thumerer et al. [68] presented a study based in East Anglia, involving the creation of a GIS based coastal risk management DSS, which adopts a Microsoft 'Visual Basic' software front-end and modelling application. The study found GIS to be suitable to ICZM, enabling integration of large databases and evaluation of interactions between a large range of factors. Building on the theme of inappropriate coastal developments, the Chinese study by Li et al. [3] incorporated a range of data types and sources within a GIS-based vulnerability assessment tool for use within spatial planning. Overall, the study found GIS to play an important role in facilitating spatial analysis of urban ecosystems and vulnerability assessments.

There are now an expanding array of web-based opportunities for interactive mapping/online cartography, facilitated by Open Data releases and Cloud service innovations [69]. This has driven a number of UK projects, such as MAREMAP [70] (The Marine Environmental Mapping Program), MEDIN [71] (The Marine Environmental Data and Information Network) and MAGIC [72] (Multi-Agency Geographic Information for the Countryside), and at the European scale, EMODNET [73] (European Marine Observation Data network). Smith [56] notes how Cloud service innovations, as well as data exploration functionalities offered by powerful and accessible, interactive mapping platforms, can work to complement Big Data analysis and Open GIS. 'Web-mapping Cloud services' are seen to have 'lower technical demands'. In particular, 'on-the-fly' rendering is reported to permit 'navigation between thousands of possible map layer variables'; Smith [56] also deems this to work in tandem with developments in Big Data allowing a diverse range of indicators (economic, demographic and environmental) to be combined. Notwithstanding that, one caveat of the advances made in this domain that Smith highlights, is that the functionality within online mapping sites is generally basic and lacks desktop geovisualisation functions.

Web-based GIS have been used in identification of coastal hazards. Moszynski et al. [74] generated a web-based Safe City & Coastal Zone GIS (SCCZ- GIS). This successfully demonstrated how real-time feeds can be combined, to monitor security effectively in the coastal zone (for people and critical infrastructure). Aside from the direct application of GIS to coastal vulnerability, another relevant example of its application, in a web-based format, is the mapping of data relating to population and demographics, which has been completed within the DataShine Census project in England [66]. This project exemplifies the positive contribution that the increasing amount of Open Source, demographic data can have, in revealing underlying geospatial patterns.

6. The application of Big Data to coastal management

For this paper, Big Data is considered as a process [43], able to facilitate evidence-based decision-making. Solutions utilising Big Data approaches can rarely be found off-the-shelf, yet Big Data software frameworks allow development of bespoke approaches to a wide range of problems [43]. Currently, there are limited examples of its application to the area of coastal management. Nevertheless, research reported in associated fields highlight its suitability to this domain.

Underlying the requirement to draw on Big Data approaches is the ever-expanding number of data sources available for coastal areas. Examples include data derived from real-time sensors and the 'internet of things', and potentially, community-sourced data, (such as volunteered geographic information (VGI)) [76]. Many initiatives are underway involving trial and validation of novel marine sensors. One such initiative is SmartBay Ireland [77] in which novel methods are being developed for collection and dissemination of real-time marine data, to national and international stakeholders. Yet the real-time nature of such data can present challenges to information systems. In relation to hydrological/oceanographic data, Big Data approaches combined with Cloud-Based solutions are regarded by Dow et al. [78], as opening opportunities for access to dynamic, up-to-date data repositories and visualisation functionality. Projects such as that conducted by Maier et al. [7] have outlined the need to combine and analyse large quantities of 'Big Data', derived from ocean sensors, utilising both archive and real-time streaming data. Their research indicates how existing methods of dealing with these large bodies of data have proved flawed. Through the cases they highlight, it is apparent that Big Data technology could transform the way that vast quantities of physical ocean data are handled. In the United States some progress has been made in terms of combining real-time sensor feeds (from large-scale monitoring networks of rivers and estuaries) together with warehoused, archive data, to enable multi-parameter modelling to take place, of dynamic interactions in aquatic ecosystems [79]. Furthermore, in 2012 the US government announced a Big Data Initiative, with $200 million devoted [80]. As part of this, 'Big Data Regional Innovation Hubs' were established. Of these, the South Big Data Hub has recently outlined coastal hazards as a priority area for future innovation [81]. Also in the US, the National Oceanic and Atmospheric Administration (NOAA) are currently undertaking work on a Big Data project (BDP) [82], in which Cloud-Based solutions are being developed for storage and processing of ocean data [83].

Chailan et al. [6] completed a study which focused on the application of High Performance Pre-Computing (HPPC) architecture to coastal flooding, in developing an alert system based on precomputed scenarios. The system they developed incorporated a web-based user application, utilising Cloud-Based solutions to enable communication with a remote cluster, permitting them to undertake statistical analysis in relation to the precomputed scenarios. The results indicated that this methodology proved valuable. Future work, building on the achievements of the project, was outlined in relation to optimisation of storage. This is one area where specific Big Data software frameworks, such as those offered by Hadoop Distributed File System (HDFS) [84] may further the advances made using HPPCs.

Big Data approaches can be viewed both in terms of the ability to store and process large volumes of data, and the advanced analytical techniques which can be applied to this data [46]. For example, the technique of 'Complex Event Processing' (CEP) [48] enables multiple data streams (including geospatial data) to be combined, so events or patterns indicating more complex situations can be inferred. In a study completed by Millie et al. [8] the deployment of advanced analytical tools, such as Machine Learning and Artificial Neural Networks (ANNs), was shown to be suitable for deriving insight from the vast array of automated sensors used for coastal monitoring, which generate large, 'high dimensional data streams'.

In the field of environmental risk, ANNs have been shown to offer potential in the realm of modelling and predicting the future financial impact of natural calamities (or extreme events) [85]. This work applied Open Source software and Cloud-based solutions, indicating that these methods could prove cost effective options for governments with limited budgets, to draw on. ANNs have also been trialled in relation to geospatial environmental data by Pijanowski et al. [86], who employed this technology in a project titled: *The Land Transformation Model*. ANNs were used to derive patterns, and combined with High Performance Computers (HPCs). This project focused on national level datasets, combined using GIS. The techniques developed within the project offer promise to coastal management, specifically in the ability to generate models of land use change and urban growth. Big Data processes present the potential to enhance the application of methods developed in such projects, for example, through implementation of 'Batch' processing techniques that can reduce the requirement for some routine, time-consuming tasks to be undertaken manually, thus improving performance [84].

Geospatial data (such as that relating to coastal areas) has been deemed particularly suited to parallel processing methods made possible using Big Data techniques [48,87,88]. Lee and Kang [48] developed a 'spatial online analytical processing' system, which allows rapid processing of spatio-temporal data. This employed PostGIS as a data warehouse and Spatial Hadoop as a base platform. As part of the research carried out by Li et al. [3], relating to Haikou City in China (see Section 4.2), Big Data analyses of social media streams (Weibo) were used to identify tourism hotspots on the coast. Li et al. found links between commercial activity, tourism, urbanisation and vulnerability. Coastal vulnerability was also found to be greater in areas where higher levels of traffic activity were recorded. Location-based service data, generated by mobile phones, is similarly being used to understand the movement of people in urban areas [89]; this technique can potentially be applied to coastal regions to monitor footfall on beaches and traffic activity on coastal roads and facilities. Another area where Big Data has been applied successfully is crisis management, especially in relation to incidents such as flooding. What has been termed 'Big Crisis Data' [90], holds promise in relation to coastal emergency incident response.

Big Data infrastructures can enable efficient storage and processing of vast amounts of coastal data. The advanced analyses that Big Data approaches offer (such as Machine Learning and data mining) make possible a better understanding of the relationship between the diverse range of variables relating to the coast. The comprehensive information outputs generated from this analysis could then form inputs for web-mapping interfaces to serve remote users (potentially through internet enabled mobile devices) [78].

7. Gaps identified in existing solutions

Information and knowledge is an integral part of ICZM and thus ICZM is seen to require an instrument for coordinated information provision [52]. Improved knowledge management has been cited as an integral component of efforts to mitigate future coastal vulnerability [3]. As such, data management can improve data value and thereby make ICZM initiatives more effective. Yet this presents a challenge with regard to data accessibility. O'Mahony et al. [53] highlight clear problems with information flows between scientists, policy makers and practitioners, hampering decisions made at the local level; implementing an evidence-base through the appropriate tools is therefore deemed a key part of any adaptation framework. The approach can permit a methodology able to tackle the issue of scientific uncertainties in social and ecological systems, which can hamper effective long-term decision making [49].

Numerous online GIS software suites now exist, such as ESRI ArcGIS Online (www.arcgis.com/home). These benefit from the potential of web-based services and Cloud-based solutions to increase access to large volumes of data stored remotely. However, despite the increasing number of Open Source mapping and data sharing projects, the data provided is often only available in a basic format, which still requires users to manipulate, analyse and generate their own visualisations from this data in order to derive insight from it [75].

In terms of risk mapping and analysis of data, a clear downfall observed in previous reported attempts relates to issues surrounding geospatial and/or temporal aggregation of data (variables). Many 'disaster risk management' decisions made at the national and international level are reported to be based on risk analysis using aggregated land-cover data [11], creating a substantial degree of uncertainty. To tackle this problem, risk mapping projects require the capability to bring a greater number of high density/attribute rich data types and sources together, providing more comprehensive representations of the variables they contain. Also in relation to scale, previous comprehensive analyses have been restricted to the level of cities or small regions, due to limitations imposed by data availability and high computing power requirements [11]. Contemporary Big Data tools and technology can potentially address these issues, enabling detailed risk mapping over wider geographical areas.

In formulating risk management strategies, there is a clear requirement to move beyond a focus limited to physical environmental datasets. Many authors, such as Nicholls et al. [1] and Spencer et al. [29], stress that a wider range of impacts now need to be incorporated within risk modelling approaches, such as health impacts arising from flooding, house price impacts [91], sophisticated impact analysis and socio-economic feedback. In line with this, Arkema et al. [41] have stressed how more work is required in developing holistic approaches, in which the adaptive role of natural habitats is recognised, as this can enable identification of locations where ecosystem-based and engineered approaches have been combined effectively. In determining future development plans, Milligan et al. [34] deem it necessary to enable planners to understand what social, cultural and economic gain, future adaptation options can offer an area. Nevertheless, many existing models are deemed lacking in that they fail to monitor the micro-economic forces associated with land use change such as human behaviour and interactions [19]. It is therefore suggested that coastal risk evaluations should incorporate a diverse range of statutory data, such as impact assessments, demographic and socio-economic information, ecological data and assessments of the role of natural habitats, evaluations of adaptation measure, and outputs from hazard models. Thus attempting to ensure evaluations are representative of the wide array of factors operating in coastal zones.

Collating wide ranging data for coastal regions is not in itself novel, yet value can be added to this process by using Big Data technologies to enable a huge body of information to be stored in a way, so that it can be accessed in (near) real-time and analysed. The analytical capabilities in particular, can enhance our understanding of coastal risk, by allowing relationships, between a wide range of data variables to be realised. To maximise the real-world relevance of such an enterprise, researchers need to consider the dynamic nature of the rapidly evolving data landscape [1]. Big Data solutions can enable a data repository/geoportal to be created, continually updated, and for real-time data feeds to be incorporated. An example of Big Data software functionality that could enable this, can be found in *Batch and Stream processing* within HDFS [45,46,84] and Apache Spark [88].

In enabling large datasets to be stored, processed and analysed in locations remote from the user, Big Data infrastructures can work to empower coastal managers by providing 'Cloud' access to huge volumes of information. Nevertheless, there are many new challenges presented by the rapidly evolving Big Data era. Among these are issues of data provenance [92], and long-term scientific stewardship of environmental and geospatial data [93].

To give a clearer indication of how Big Data solutions identified within this research address the problems and opportunities discussed, Table 1 draws together key themes covered, pertaining to coastal risk management.

8. Conclusion

Records of previous and on-going projects reveal how coastal data has been used effectively within DSS, risk studies and Open Source mapping projects. The numerous examples of GIS application to coastal regions, combined with the emerging opportunities afforded by the Big Data approaches outlined, indicate that this is an area where geospatial Big Data analysis can potentially transform coastal planning processes. Big Data does not provide a standalone solution to the issues and gaps outlined above. However, it does potentially provide a framework in which the large volumes and varieties of coastal datasets can be collated and analysed, particularly in the context of the current trend towards geoportal development and the growing awareness of the need for key authoritative integrated land/marine datasets – recognised as a fundamental enabler to good management of the coastal zone. Past coastal assessments have been noted to involve subjective judgements [24,38,42,94], and in some cases this has reduced stakeholder confidence in the outputs they have generated. By enabling such a wide

Table 1
Summary of key themes in risk-based decision making in coastal regions.

	Theme	Problem context: coastal risk adaptation	Opportunity: data-driven approaches	Proposed solution: application of big data to coastal management
Environmental	The role of ecosystems and nature	1. Requirement to shift from 'Hard' to 'Soft' adaptation measures [19,20] 2. Recognition of the role of natural defences and ecosystem services [3] 3. Recommendations for future nature based adaptation measures [2,4] 4. Natural and manmade defences both critical in controlling the extent of flooding [5] 5. Need to identify where ecosystem and engineering approaches have been combined successfully [6]	1. Evaluation of the role of natural defences is inadequate [6], evaluation of data and modelling required 2. Holistic approaches (drawing a wide range of data) required to account for the adaptive role of natural habitats [6] 3. Need to account for interactions between factors, can enhance understanding of nature, such as the 2D hydrodynamic or sediment transport processes operating in the nearshore environment [7].	1. Complex interactions between factors, such as urbanisation and ecosystems, can be revealed [8]. 2. Better understand relationships between the diverse range of data variables 3. High density/attribute rich data streams from real-time hydrological sensor networks can be incorporated within analysis [9] 4. Geomorphological change derived from analysis of high resolution environmental monitoring data
	Socio-economic context	1. Population growth a catalyst factor, resulting in vulnerable assets, people, and infrastructure [10,11] 2. Human induced hazards need accounting for, that can create coastal squeeze and a sand-starved coast [32]	1. Data is required detailing the consequences of flooding and erosion [1] 2. Knowledge of vulnerability can enable communities to respond to threats [5]	1. Enable development of alert systems for flooding [13] 2. Facilitate coastal emergency incident response [14] 3. Enable multi-parameter modelling of dynamic interactions between factors [8]
	Coastal risk	1. Risk = probability x consequences [1,4,15–22] 2. Requirement to consider both risk to humans and the environment 3. Flooding and Erosion are major hazards 4. Flood risk seen to rise fastest [23]	1. Hazards need to be modelled and impacts predicted, to evaluate the full range of risks 2. Need to develop vulnerability indices [15, p. 282] 3. Modelling of data enables responses to be developed to natural calamities [25]	1. Enable representative risk profiles to be generated 2. Inclusion of high resolution data in wide scale national level analysis [26] 3. Reduce uncertainty –allow coastal risk assessment parameters to be derived from the data
Societal/institutional responses and governance	Risk perception	1. Fundamental lack of understanding of natural processes [46] 2. Need to increase stakeholder confidence in policy based on analytical outputs 3. Coastal protection measures can produce inverse incentives to settle in high risk areas [28]	1. Data driven modelling underlies science [15] 2. Scientific understanding of dynamic coastal processes needs to be clearly communicated [29,30]. 3. Risk assessment needs to account for a wide range of elements otherwise risk perception bias can ensue [17]	1. Can link high resolution data, flood modelling and visualisation tools [31] 2. Ability to tap into unconventional data sources 3. Mining of social media streams [32] to derive public perceptions
	Coastal management	1. Information flows between scientists, policy makers and planners can hamper decision making [33] 2. Government responsibility to inform public about coastal risk [16]	1. Data is the foundation of the knowledge base for ICZM [33] 2. Extensive guidelines for environmental data management initiatives [34], especially relating to ICZM [3,35] 3. ICZM requires an instrument for coordinated data provision [35]	1. Can provide access for coastal managers, to large quantities of data stored remotely 2. Allow novel forms of data to be included in assessments such as mobile phone positioning data [36], revealing footfall on beaches, traffic flow densities, tourist and commercial activity, etc.
	Spatial planning	1. Reduce vulnerability by ensuring future developments are sustainable [16] 2. Requirement to reveal interactions between factors impacting land use [16] 3. Details of coastal risk provided in planning guidance 4. [37] 5. Planners need to understand social, cultural, economic gain future adaptation options offer [38]	1. Data-driven risk assessment can enable evaluation of available planning options [39] 2. Implementation of data management through spatial planning is key to ICZM [33] 3. Vulnerability assessment tools are required in spatial planning [32] 4. Data can enable monitoring of forces associated with land use change [16]	1. Enable inclusion of detailed property level data in assessments 2. Automated processes enable patterns to be derived of land use change and urban growth [26] 3. Allow comprehensive analysis at wider scales
Technological	Geospatial and temporal GIS and Decision Support	1. Evidence based assessments need to identify vulnerable locations [37] 2. Risk management in the coastal zone is a geospatial issue [11]	1. GIS is used extensively in DSS and vulnerability assessments [3,38,63,65] 2. GIS can combine many social and environmental data layers [39] 3. Draw on web-mapping and Cloud services [42] 4. Web-mapping interfaces can enable data to be made available to remote users [43] 5. Open geospatial data available, via online portals:	1. Big Data system proven application to geospatial data [44–46] 2. Big Data can build on advances in web-mapping and Cloud-based solutions [47] 3. Enable large bodies of Open Source data to be collated in data repositories/geoportals 4. Unlock the benefits of some suitable DSS tools (Section 5.3)

(continued on next page)

Table 1 (continued)

Theme	Problem context: coastal risk adaptation	Opportunity: data-driven approaches	Proposed solution: application of big data to coastal management
		MEDIN/EMODNET (Section 5.4)	
Information requirements	1. Need to tackle scientific uncertainties in social and ecological system, which hamper decision making [27] 2. Need to reduce subjectivity in coastal risk assessments and planning (inherent in some past assessments [22,48–50]) 3. Requirement for robust risk profiles derived from reliable data	1. Comprehensive analysis hinges on the availability, accuracy and resolution of appropriate data [31] 2. Combining hazard datasets with property level data can enable national level risk mapping [28] 3. Data required for large spatial-temporal extents 4. Aggregation of data variables in assessments can equal uncertainty [51] 5. Integration required of marine and terrestrial datasets (many of which are Open Source Public Sector Information (PSI))	1. Big Data frameworks offer advances in data storage, processing power and speed [52] 2. Enable creation of up to data repositories (including large bodies of data derived from Ocean Sensors [9]) 3. Better understand relationships between diverse range of data variables. 4. Enable storage, processing and analysis of high resolution datasets, combining scale and detail, moving beyond aggregation of data 5. Enable reuse of large volumes of PSI using Spatial Data Infrastructure (SDI), such as INSPIRE [34]
Technological capabilities	1. Requirement for more comprehensive representation of processes taking place in the coastal zone [1] 2. Need to consider a wide range of factors in any analysis, and interactions between these, including the social and economic context [17,44]	1. DSS can be constrained by the ability to handle large quantities, types and density of data [53]. 2. Knowledge in this domain is reliant on data being continuously collected and analysed (temporally representative) [54]	1. Heterogeneous data types and sources can be combined and data-mining techniques applied to them [55,56] 2. Advanced analysis, such as Machine Learning and ANNs, used to derive insight and realise relationships, from high-dimensional data streams [57] 3. Inclusion of real-time streaming data with archive data (via Batch and Stream capabilities) [58]

range of data representing a complex array of factors, to be combined, Big Data technologies can potentially allow assessment criteria to be derived from reliable data. This new generation of Big Data approaches can tackle uncertainty through enabling robust environmental risk profiles to be generated for coastal regions.

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References

[1] R.J. Nicholls, R.J. Dawson, S.A. Day (Eds.), Broad Scale Coastal Simulation, Springer, Netherlands, Dordrecht, 2015, , http://dx.doi.org/10.1007/978-94-007-5258-0.

[2] M. Mokrech, S. Hanson, R.J. Nicholls, J. Wolf, M. Walkden, C.M. Fontaine, S. Nicholson-Cole, S.R. Jude, J. Leake, P. Stansby, A.R. Watkinson, M.D.a. Rounsevell, J.a. Lowe, J.W. Hall, The Tyndall coastal simulator, J. Coast. Conserv. 15 (2011) 325–335, http://dx.doi.org/10.1007/s11852-009-0083-6.

[3] Y. Li, X. Zhang, X. Zhao, S. Ma, H. Cao, J. Cao, Assessing spatial vulnerability from rapid urbanization to inform coastal urban regional planning, Ocean Coast. Manag. 123 (2016) 53–65, http://dx.doi.org/10.1016/j.ocecoaman.2016.01.010.

[4] H. de Moel, B. Jongman, H. Kreibich, B. Merz, E. Penning-Rowsell, P.J. Ward, Flood risk assessments at different spatial scales, Mitig. Adapt. Strateg. Glob. Changes 20 (2015) 865–890, http://dx.doi.org/10.1007/s11027-015-9654-z.

[5] Halcrow Group, Risk Assessment of Coastal Erosion Part One, Department for Environment Farming and Rural Affairs and Environment Agency (R & D Technical Report FD2324/TR1), 2007.

[6] R. Chailan, F. Bouchette, C. Dumontier, O. Hess, A. Laurent, O. Lobry, H. Michaud, S. Nicoud, G. Toulemonde, High performance pre-computing: prototype application to a coastal flooding decision tool, − in: Proceedings of the 4th International Conference Knowl. Syst. Eng., KSE, 2012, 7. ⟨http://dx.doi.org/10.1109/KSE.2012.36⟩.

[7] D. Maier, V.M. Megler, A.M. Baptista, A. Jaramillo, C. Seaton, P.J. Turner, Navigating oceans of data, in: Proceedings of the Sci. Stat. Database Manag. Conf., 2012, pp. 1–19. doi: ⟨http://dx.doi.org/10.1007/978-3-642-31235-9_1⟩.

[8] D.F. Millie, G.R. Weckman, W.A. Young, J.E. Ivey, D.P. Fries, E. Ardjmand, G.L. Fahnenstiel, Coastal "Big Data" and nature-inspired computation: prediction potentials, uncertainties, and knowledge derivation of neural networks for an algal metric, Estuar. Coast. Shelf Sci. 125 (2013) 57–67, http://dx.doi.org/10.1016/j.ecss.2013.04.001.

[9] W. Kron, Coasts: the high-risk areas of the world, Nat. Hazards 66 (2013) 1363–1382, http://dx.doi.org/10.1007/s11069-012-0215-4.

[10] M. Muro, S.E. Hrudey, S. Jude, L. Heath, S. Pollard, Making it real: what risk managers should know about community engagement, J. Environ. Assess. Policy Manag. 14 (2012) 1–21, http://dx.doi.org/10.1142/S146433321250010X.

[11] B. Jongman, E.E. Koks, T.G. Husby, P.J. Ward, Increasing flood exposure in the Netherlands: implications for risk financing, Nat. Hazards Earth Syst. Sci. 14 (2014) 1245–1255, http://dx.doi.org/10.5194/nhess-14-1245-2014.

[12] R. Misdorp, Climate of Coastal Cooperation, Leiden, The Netherlands, 2011. ⟨http://www.coastalcooperation.net/part-0/index.htm⟩.

[13] B. Smit, J. Wandel, Adaptation, adaptive capacity and vulnerability, Glob. Environ. Changes 16 (2006) 282–292, http://dx.doi.org/10.1016/j.gloenvcha.2006.03.008.

[14] Defra, Making Space for Water: Taking Forward a New Government Strategy for Flood and Coastal Erosion Risk Management, London, 2005.

[15] Defra, Making Space for Water: Developing a New Government Strategy for Flood and Coastal Erosion Risk Management in England, London, 2004.

[16] R.S. Roberts, Economic Strategies for Coastal Disaster Risk-Reduction: A Case Study of Exmouth (Ph.D.), Murdoch University, Western Australia, 2012.

[17] W.J.W. Botzen, J.C.J.M. van den Bergh, Insurance against climate change and flooding in the Netherlands: present, future, and comparison with other countries, Risk Anal. 28 (2008) 413–426, http://dx.doi.org/10.1111/j.1539-6924.2008.01035.x.

[18] Goverment Office for Science, Foresight Future Flooding, 2004. ⟨https://www.gov.uk/government/publications/future-flooding⟩.

[19] T. Filatova, A. Veen, Microeconomic Motives of Land Use Change in Coastal Zone Area: Agent Based Modelling Approach, 2006. ⟨http://doc.utwente.nl/61124/1/Filatova07micro.pdf⟩.

[20] T. Filatova, J.P.M. Mulder, A. Veen, Coastal risk management: how to motivate individual economic decisions to lower flood risk? Ocean Coast. Manag. 54 (2011) 164–172, http://dx.doi.org/10.1016/j.ocecoaman.2010.10.028.

[21] O.G. Dávila, M. Stithou, G. Pescaroli, L. Pietrantoni, P. Koundouri, P. Díaz-Simal,

B. Rulleau, N. Touili, F. Hissel, E. Penning-Rowsell, Promoting resilient economies by exploring insurance potential for facing coastal flooding and erosion: evidence from Italy, Spain, France and United Kingdom, Coast. Eng. 87 (2014) 183–192, http://dx.doi.org/10.1016/j.coastaleng.2013.12.007.
[22] Defra, Appraisal of Flood and Coastal Erosion Risk Management. A DEFRA Policy Statement, 2009. ⟨https://www.gov.uk/government/publications/appraisal-of-flood-and-coastal-erosion-risk-management-a-defra-policy-statement-june-2009⟩.
[23] W. Dodds, An Evaluation of Coastal Risk Decision Making in England, Wales and Northern Ireland (Ph.D.), Cardiff University, Ann Arbor, MI, 2009.
[24] C. Viavattene, J.A. Jiminez, D. Owen, S. Priest, D. Parker, A.P. Micou, S. Ly, Resilience-increasing Strategies for Coasts – Coastal Risk Assessment Framework Guidance Document, 2015.
[25] R.J. Dawson, M.E. Dickson, R.J. Nicholls, J.W. Hall, M.J.A. Walkden, P.K. Stansby, M. Mokrech, J. Richards, J. Zhou, J. Milligan, A. Jordan, S. Pearson, J. Rees, P.D. Bates, S. Koukoulas, A.R. Watkinson, Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change, Clim. Change 95 (2009) 249–288, http://dx.doi.org/10.1007/s10584-008-9532-8.
[26] G.W. Boehlert, A.B. Gill, Environmental and ecological effects of ocean renewable energy development: a current synthesis, Oceanography 23 (2008) 68–81, http://dx.doi.org/10.5670/oceanog.2010.46.
[27] C. Heip, M. Barange, R. Danovaro, M. Gehlen, A. Grehan, F. Meysman, T. Oguz, V. Papathanassiou, C. Philippart, J. She, P. Tréguer, Climate Change and Marine Ecosystem Research Synthesis of European Research on the Effects of Climate Change on Marine Environments, Ostend, Belgium, 2011.
[28] P.W. French, Coastal Defences: Processes, Problems and Solutions, Routledge, London, 2001.
[29] T. Spencer, S.M. Brooks, B.R. Evans, J.A. Tempest, I. Möller, Southern North Sea storm surge event of 5 December 2013: water levels, waves and coastal impacts, Earth-Sci. Rev. 146 (2015) 120–145, http://dx.doi.org/10.1016/j.earscirev.2015.04.002.
[30] M.P. Wadey, I.D. Haigh, R.J. Nicholls, J.M. Brown, K. Horsburgh, B. Carroll, S.L. Gallop, T. Mason, E. Bradshaw, A comparison of the 31 January–1 February 1953 and 5–6 December 2013 coastal flood events around the UK, Front. Mar. Sci. 2 (2015) 1–27, http://dx.doi.org/10.3389/fmars.2015.00084.
[31] J.A.G. Cooper, J. McKenna, Boom and bust: the influence of macroscale economics on the world's coasts, J. Coast. Res. 253 (2009) 533–538, http://dx.doi.org/10.2112/09A-0001.1.
[32] UNISDR, Global Assessment Report on Disaster Risk Reduction – Revealing Risk, Redefining Development, Geneva, 2011. ⟨http://www.preventionweb.net/english/hyogo/gar/2011/en/bgdocs/GAR-2011/GAR2011_Report_Prelims.pdf⟩.
[33] B. Zanuttigh, D. Simcic, S. Bagli, F. Bozzeda, L. Pietrantoni, F. Zagonari, S. Hoggart, R.J. Nicholls, THESEUS decision support system for coastal risk management, Coast. Eng. 87 (2014) 218–239, http://dx.doi.org/10.1016/j.coastaleng.2013.11.013.
[34] J. Milligan, T. O'Riordan, S.A. Nicholson-Cole, A.R. Watkinson, Nature conservation for future sustainable shorelines: lessons from seeking to involve the public, Land Use Policy 26 (2009) 203–213, http://dx.doi.org/10.1016/j.landusepol.2008.01.004.
[35] M. Villatoro, R. Silva, F.J. Méndez, B. Zanuttigh, S. Pan, E. Trifonova, I.J. Losada, C. Izaguirre, D. Simmonds, D.E. Reeve, E. Mendoza, L. Martinelli, S.M. Formentin, P. Galiatsatou, P. Eftimova, An approach to assess flooding and erosion risk for open beaches in a changing climate, Coast. Eng. 87 (2014) 50–76, http://dx.doi.org/10.1016/j.coastaleng.2013.11.009.
[36] B. Jongman, H. Kreibich, H. Apel, J.I. Barredo, P.D. Bates, L. Feyen, A. Gericke, J. Neal, J.C.J.H. Aerts, P.J. Ward, Comparative flood damage model assessment: towards a European approach, Nat. Hazards Earth Syst. Sci. 12 (2012) 3733–3752, http://dx.doi.org/10.5194/nhess-12-3733-2012.
[37] The Natural Capital Project, Coastal Vulnerability Model, 2015, 1. ⟨http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/coastal_vulnerability.html⟩. (Accessed 28 January 2016).
[38] S. McLaughlin, J.A.G. Cooper, A multi-scale coastal vulnerability index: a tool for coastal managers? Environ. Hazards 9 (2010) 233–248, http://dx.doi.org/10.3763/ehaz.2010.0052.
[39] E. Ramieri, A. Hartley, A. Barbanti, F.D. Santos, A. Gomes, M. Hilden, P. Laihonen, N. Marinova, M. Santini, Methods for Assessing Coastal Vulnerability to Climate Change, Bologna (IT), 2011. ⟨http://www.oannes.org.pe/upload/201204171418031650971105.pdf⟩.
[40] The United Nations, Global Sustainable Development Report, 2015. ⟨https://sustainabledevelopment.un.org/content/documents/1758GSDR2015AdvanceUneditedVersion.pdf⟩.
[41] K.K. Arkema, G. Guannel, G. Verutes, S.a. Wood, A. Guerry, M. Ruckelshaus, P. Kareiva, M. Lacayo, J.M. Silver, Coastal habitats shield people and property from sea-level rise and storms, Nat. Clim. Changes 3 (2013) 913–918, http://dx.doi.org/10.1038/nclimate1944.
[42] S. Westmacott, Developing decision support systems for integrated coastal management in the tropics: is the ICM decision-making environment too complex for the development of a useable and useful DSS? J. Environ. Manag. 62 (2001) 55–74, http://dx.doi.org/10.1006/jema.2001.0420.
[43] B. Marr, Big Data: Using SMART Big Data, Analytics and Metrics to Make Better Decisions and Improve Performance, Wiley, Cichester, 2015.
[44] H.V. Jagadish, Big data and science: myths and reality, Big Data Res. 2 (2015) 49–52, http://dx.doi.org/10.1016/j.bdr.2015.01.005.
[45] S. Gao, L. Li, W. Li, K. Janowicz, Y. Zhang, Constructing gazetteers from volunteered Big Geo-Data based on Hadoop, Comput. Environ. Urban Syst. 61 (2014) 172–186, http://dx.doi.org/10.1016/j.compenvurbsys.2014.02.004.
[46] V. Snasel, J. Kacprzyk, Big Data in Complex Systems, 9th ed., Springer International Publishing, eBook, Switzerland, 2015.
[47] R. Kitchin, Big data and human geography: opportunities, challenges and risks, Dialog. Hum. Geogr. 3 (2013) 262–267, http://dx.doi.org/10.1177/2043820613513388.
[48] J.-G. Lee, M. Kang, Geospatial Big Data: challenges and opportunities, Big Data Res. 2 (2015) 74–81, http://dx.doi.org/10.1016/j.bdr.2015.01.003.
[49] R. Brennan, The North Norfolk coastline: a complex legacy, Coast. Manag. 35 (2007) 587–599, http://dx.doi.org/10.1080/08920750701593428.
[50] J. Rochette, R. Billé, ICZM protocols to regional seas conventions: what? Why? How? Mar. Policy 36 (2012) 977–984, http://dx.doi.org/10.1016/j.marpol.2012.02.014.
[51] IOC/UNESCO, IMO, FAO, UNDP, A Blueprint for Ocean and Coastal Sustainability, Paris, 2011.
[52] B. Dyer, K. Millard, A generic framework for value management of environment data in the context of integrated coastal zone management, Ocean Coast. Manag. 45 (2002) 59–75, http://dx.doi.org/10.1016/S0964-5691(02)00046-7.
[53] C. O'Mahony, S. Gray, J. Gault, V. Cummins, ICZM as a framework for climate change adaptation action – experience from Cork Harbour, Ireland, Mar. Policy (2015) 1–10, http://dx.doi.org/10.1016/j.marpol.2015.10.008.
[54] C.E. Landry, A.G. Keeler, W. Kriesel, An economic evaluation of beach erosion management alternatives university of Maryland, Mar. Resour. Econ. 18 (2003) 105–127.
[55] M.P. Wadey, S.N. Cope, R.J. Nicholls, K. McHugh, G. Grewcock, T. Mason, Coastal flood analysis and visualisation for a small town, Ocean Coast. Manag. 116 (2015) 237–247, http://dx.doi.org/10.1016/j.ocecoaman.2015.07.028.
[56] D.A. Smith, Online interactive thematic mapping: applications and techniques for socio-economic research, Comput. Environ. Urban Syst. 57 (2016) 106–117, http://dx.doi.org/10.1016/j.compenvurbsys.2016.01.002.
[57] E. Bigagli, The international legal framework for the management of the global oceans social-ecological system, Mar. Policy 68 (2016) 155–164, http://dx.doi.org/10.1016/j.marpol.2016.03.005.
[58] L.D. Rodwell, S. Fletcher, G.A. Glegg, M. Campbell, S.E. Rees, M. Ashley, E.A. Linley, M. Frost, B. Earll, R.B. Wynn, L. Mee, P. Almada-Villela, D. Lear, P. Stanger, A. Colenutt, F. Davenport, N.J. Barker Bradshaw, R. Covey, Marine and coastal policy in the UK: challenges and opportunities in a new era, Mar. Policy 45 (2014) 251–258, http://dx.doi.org/10.1016/j.marpol.2013.09.014.
[59] European Commission, Directive 2007/2/EC of the European Parliament and of the council of 14 March 2007 Establishing an Infrastructure for Spatial Information in the European Community (INSPIRE), Off. J. Eur. Union, 50, 2007 1–14. ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?Uri = OJ:L:2007:108:0001:0014:EN:PDF⟩.
[60] C.A. Keay, S.H. Hallett, T.S. Farewell, A.P. Rayner, R.J.A. Jones, Moving the national soil database for England and Wales (LandIS) towards inspire compliance, Int. J. Spat. Data Infrastruct. Res. 4 (2009) 134–155, http://dx.doi.org/10.2902/1725-0463.2009.04.art8.
[61] European Commission, D2.8.III.3 Data Specification on Soil – Draft Technical Guidelines: INSPIRE Infrastructure for Spatial Information in Europe, 2013. ⟨http://inspire.ec.europa.eu/documents/Data_Specifications/INSPIRE_DataSpecification_SO_v3.0rc3.pdf⟩.
[62] J. Georis-Creuseveau, C. Claramunt, F. Gourmelon, A modelling framework for the study of spatial data infrastructures applied to coastal management and planning, Int. J. Geogr. Inf. Sci. 31 (2017) 122–138, http://dx.doi.org/10.1080/13658816.2016.1188929.
[63] The National Trust, Shifting Shores, 2015. ⟨https://www.nationaltrust.org.uk/documents/shifting-shores-report-2015.pdf⟩. (Accessed 28 January 2016).
[64] A. van Dongeren, P. Ciavola, C. Viavattene, S. de Kleermaeker, G. Martinez, O. Ferreira, C. Costa, R. McCall, RISC-KIT: resilience-increasing strategies for coasts – toolKIT, J. Coast. Res. (2014) 366–371, http://dx.doi.org/10.2112/si70-062.1.
[65] S. Torresan, A. Critto, J. Rizzi, A. Zabeo, E. Furlan, A. Marcomini, DESYCO: a decision support system for the regional risk assessment of climate change impacts in coastal zones, Ocean Coast. Manag. 120 (2016) 49–63, http://dx.doi.org/10.1016/j.ocecoaman.2015.11.003.
[66] K.K. Arkema, G.M. Verutes, S.A. Wood, C. Clarke-Samuels, S. Rosado, M. Canto, A. Rosenthal, M. Ruckelshaus, G. Guannel, J. Toft, J. Faries, J.M. Silver, R. Griffin, A.D. Guerry, Embedding ecosystem services in coastal planning leads to better outcomes for people and nature, Proc. Natl. Acad. Sci. USA 112 (2015) 201406483, http://dx.doi.org/10.1073/pnas.1406483112.
[67] R. Nicholls, A. Bradbury, H. Burningham, J. Dix, M. Ellis, J. French, J. Hall, H. Karunarathna, J. Lawn, S. Pan, D. Reeve, B. Rogers, A. Souza, P. Stansby, J. Sutherland, O. Tarrant, M. Walkden, R. Whitehouse, iCOASST–integrating coastal sediment systems, Coast. Eng. Proc. 1 (2012) 100.
[68] T. Thumerer, A.P. Jones, D. Brown, A. GIS, based coastal management system for climate change associated flood risk assessment on the east coast of England, Int. J. Geogr. Inf. Sci. 14 (2000) 265–281, http://dx.doi.org/10.1080/136588100240840.
[69] W. Tang, W. Feng, Parallel map projection of vector-based big spatial data: coupling cloud computing with graphics processing units, Comput. Environ. Urban Syst. 61 (2014) 187–197, http://dx.doi.org/10.1016/j.compenvurbsys.2014.01.001.
[70] MAREMAP, The Marine Environmental Mapping Program, n.d. ⟨http://www.maremap.ac.uk/index.html⟩. (Accessed 17 March 2017).
[71] MEDIN, The Marine Environmental Data and Information Network, n.d. ⟨http://www.oceannet.org/about_us/⟩. (Accessed 17 March 2017).
[72] MAGIC, Multi-Agency Geographic Information for the Countryside, n.d. ⟨http://magic.defra.gov.uk/home.htm⟩. (Accessed 17 March 2017).

[73] EMODnet; European Marine Observation Data network, n.d. 〈http://www.emodnet.eu/〉. (Accessed 17 March 2017).
[74] M. Moszynski, M. Kulawiak, A. Chybicki, K. Bruniecki, T. Bieliński, Z. Łubniewski, A. Stepnowski, Innovative web-based geographic information system for municipal areas and coastal zone security and threat monitoring using EO satellite data, Mar. Geod. 38 (2015) 203–224, http://dx.doi.org/10.1080/01490419.2014.969459.
[75] O. O'Brien, J. Cheshire, Interactive mapping for large, open demographic data sets using familiar geographical features, J. Maps 5647 (2015) 1–8, http://dx.doi.org/10.1080/17445647.2015.1060183.
[76] R. Devillers, D.M. De Freitas, The use of GIS and geospatial technologies in support of coastal zones management – results of an international survey, in: Proceedings of the 11th International Symp. GIS Comput. Cartogr. Coast. Zo. Manag., CoastGIS, Victoria, British Columbia, Canada, 2013, pp. 100–103. 〈http://ro.uow.edu.au/cgi/viewcontent.cgi?Article = 2125&context = lhapapers〉.
[77] SmartBay, Ireland, 2017. 〈http://www.smartbay.ie/〉. (Accessed 15 May 2017).
[78] A.K. Dow, E.M. Dow, T.D. Fitzsimmons, M.M. Materise, Harnessing the environmental data flood: a comparative analysis of hydrologic, oceanographic, and meteorological informatics platforms, Bull. Am. Meteorol. Soc. 96 (2015) 725–736, http://dx.doi.org/10.1175/BAMS-D-13-00178.1.
[79] H.R. Kolar, J. Cronin, P. Hartswick, a.C. Sanderson, J.S. Bonner, L. Hotaling, R.F. Ambrosio, Z. Liu, M.L. Passow, M.L. Reath, Complex real-time environmental monitoring of the Hudson River and estuary system, IBM J. Res. Dev. 53 (4) (2009) 1–4, http://dx.doi.org/10.1147/JRD.2009.5429017.
[80] The White House, Press Release: Obama Administration Unveils 'Big Data' Initiative: Announces $200 Million in New R & D Investments, 2012. 〈https://obamawhitehouse.archives.gov/the-press-office/2015/11/19/release-obama-administration-unveils-big-data-initiative-announces-200〉. (Accessed 6 March 2017).
[81] The South Big Data Hub, 2017. 〈http://www.southbdhub.org/〉. (Accessed 6 March 2017).
[82] NOAA, Big Data Project, National Oceanic and Atmospheric Administration, 2017. 〈http://www.noaa.gov/big-data-project〉. (Accessed 6 March 2017).
[83] J. Sundwall, B. Bouffler, The NOAA big data project: NEXRAD on the cloud, in: EGU Gen. Assem, Vienna Austria, 2016, p. 2156.
[84] N. Marz, J. Warren, Big Data: Principles and Best Practices of Scalable Realtime Data Systems, 2015〈http://dl.acm.org/citation.cfm?Id = 2717065〉. (Accessed 24 January 2016).
[85] C.K. Joseph, S. Kakade, Predicting impact of natural calamities in era of big data and data science, in: Proceedings of the International Environ. Model. Softw. Soc. 7th International Congr. Env. Model. Softw., San Diego, CA, USA, 2014.
[86] B.C. Pijanowski, A. Tayyebi, J. Doucette, B.K. Pekin, D. Braun, J. Plourde, A big data urban growth simulation at a national scale: configuring the GIS and neural network based land transformation model to run in a high performance computing (HPC) environment, Environ. Model. Softw. 51 (2014) 250–268, http://dx.doi.org/10.1016/j.envsoft.2013.09.015.
[87] C. Yang, M. Yu, F. Hu, Y. Jiang, Y. Li, Utilizing cloud computing to address big geospatial data challenges, Comput. Environ. Urban Syst. 61 (2017) 120–128, http://dx.doi.org/10.1016/j.compenvurbsys.2016.10.010.
[88] J. Yu, W. Jinxuan, S. Mohamed, GeoSpark, A. Cluster Computing, Framework for processing large-scale spatial data, in: Proceedings of the 23th International Conference on Adv. Geogr. Inf. Syst., 2015, 4–7. doi: 〈http://dx.doi.org/10.1145/2820783.2820860〉.
[89] C. Ratti, D. Frenchman, R.M. Pulselli, S. Williams, Mobile landscapes: using location data from cell phones for urban analysis, Environ. Plan. B Plan. Des. 33 (2006) 727–748, http://dx.doi.org/10.1068/b32047.
[90] J. Qadir, A. Ali, R. ur Rasool, A. Zwitter, A. Sathiaseelan, J. Crowcroft, Crisis analytics: big data-driven crisis response, J. Int. Humanit. Action 1 (2016) 12, http://dx.doi.org/10.1186/s41018-016-0013-9.
[91] Y. Chen, B. Fingleton, G. Pryce, A.S. Chen, S. Djordjević, Implications of rising flood-risk for employment location: a GMM spatial model with agglomeration and endogenous house price effects, J. Prop. Res. 30 (2013) 298–323, http://dx.doi.org/10.1080/09599916.2013.765499.
[92] B. Glavic, Big Data Provenance: Challenges and Implications for Benchmarking, Springer, Berlin Heidelberg, 2014, http://dx.doi.org/10.1007/978-3-642-53974-9_7.
[93] G. Peng, N.A. Ritchey, K.S. Casey, E.J. Kearns, J.L. Privette, D. Saunders, P. Jones, T. Maycock, S. Ansari, Scientific stewardship in the open data and big data era – roles and responsibilities of stewards and other major product stakeholders, D-Lib. Mag. 22 (2016), http://dx.doi.org/10.1045/may 2016-peng.
[94] N. Smith, Why One Size Won't Fit All: Key Messages from the C-SCOPE Project, 2012.
[95] 〈data.gov.uk〉, n.d. 〈https://data.gov.uk/〉. (Accessed 17 March 2017).
[96] M.J.A. Walkden, J.W. Hall, A predictive mesoscale model of the erosion and profile development of soft rock shores, Coast. Eng. 52 (2005) 535–563, http://dx.doi.org/10.1016/j.coastaleng.2005.02.005.
[97] I. Brown, S. Jude, S. Koukoulas, R. Nicholls, M. Dickson, M. Walkden, Dynamic simulation and visualisation of coastal erosion, Comput. Environ. Urban Syst. 30 (2006) 840–860, http://dx.doi.org/10.1016/j.compenvurbsys.2005.08.002.
[98] M. Walkden, K. Rossington, Characterisation and Prediction of Large-scale Long Term Change of Coastal Geomorphological Behaviours Proof of Concept Modelling, 2009. 〈http://copac.ac.uk/search?Rn = 19&any = great + britain&ti = coastal + erosion&sort-order = ti,-date〉.
[99] iCOASST, integrating COASTal Sediment Systems, n.d. 〈http://www.icoasst.net/〉. (Accessed 17 March 2017).
[100] PEARL, Preparing for Extreme And Rare events in coastaL regions, n.d. 〈http://www.pearl-fp7.eu/〉. (Accessed 17 March 2017).
[101] Z. Vojinovic, Y. Abebe, A. Sanchez, N.M. Pena, I. Nikolic, N. Monojlovic, C. Makropoulos, M. Pelling, M. Abbott, Holistic flood risk assessment in coastal areas – the PEARL approach, in: Proceedings of the 11th International Conference on Hydroinformatics, 2014, pp. 1–8.
[102] THESEUS Project, Innovative Technologies for Safer European Coasts in a Changing Climate, n.d. 〈http://www.theseusproject.eu/〉. (Accessed 17 March 2017).
[103] C-SCOPE, Combining Sea and Coastal Planning in Europe, n.d. 〈http://www.cscope.eu/en/〉. (Accessed 17 March 2017).
[104] RISC-KIT, Resilience-increasing Strategies for Coasts–toolkit, n.d. 〈http://www.risckit.eu/np4/aboutPartnerships/〉. (Accessed 17 March 2017).